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the race any further and no longer possible to separate two distinct races by selection without a cross with normal.

The conclusions that logically follow from the preceding discussion are that (1) extra bristles are primarily occasioned by one germinal unit and further influenced by other germinal units, and (2) that no change that could have either evolutionary or practical significance has occurred in these units during the 50 generations of the experiment.

¹ Pearl, R., *J. Exp. Zool., Philadelphia*, 13, 1912, (283-394); Nilsson, Hj., see De Vries, *Plant Breeding*; De Vries, H., *The Mutation Theory*; Tower, W. L., *Washington, Pub. Carnegie Inst.*, No. 48; Johannsen, W., *Elemente der Exakten Erblchkeitslehre*.

² Castle, W. E., and Phillips, J. C., *Washington, Pub. Carnegie Inst.*, No. 195; Smith, L. H., *Univ. Ill. Agric. Exp. Sta. Bull.*, No. 128; Middleton, R., *J. Exp. Zool., Philadelphia*, 19, (451-503); Jennings, H. S., *Genetics, Cambridge*, 1, (407-534).

³ MacDowell, E. C., *J. Exp. Zool., Philadelphia*, 19, (61-98).

⁴ Castle, W. E., and Wright, S., *Washington, Pub. Carnegie Inst.*, No. 241.

PRESSURE PHENOMENA ACCOMPANYING THE GROWTH OF CRYSTALS

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Under suitable conditions crystals grow in directions in which growth is opposed by external force. This fact appears to have been first observed by Lavalley in 1853.¹ It was denied, however by Kopp, who, after making certain experiments, stated that he was never able to observe anything tending to confirm the view that a crystal can raise itself in order to grow also on the side on which it rests.² Subsequently the observations of Lavalley were confirmed by Lehmann³ and others.

Becker and Day seem to have made the first attempt at determining the magnitude of the force developed during crystal growth. In their experiment, a crystal of alum supporting a weight was covered with a saturated solution of alum, and supersaturation was induced by evaporation. The crystal increased in size through growth on the lateral exposed faces which were also extended downward, thus lifting the crystal together with its load. The deposition of new material on the lower surface was restricted to the periphery, so that a hollow face was gradually formed by the downward extension of the new growth, and the crystal rested on a very narrow outer rim. The area of this rim was determined with difficulty, but repeated measurements led to the conclusion that "the force per unit area which the crystals exert . . .

is of the same order of magnitude as the ascertained resistance which the crystals offered to crushing stresses.”⁴

In 1913 Bruhns and Mecklenburg published a paper⁵ in which they claim to have repeated the experiment of Becker and Day with negative results. In a reply to this paper Becker and Day explain the different results obtained by Bruhns and Mecklenburg as due to the fact that the original experiment was not duplicated.⁶ This conclusion was reached independently by the present writer.⁷ By placing an unloaded crystal in the same solution with the loaded one supersaturation with respect to the supporting surface of the loaded crystal was prevented.

Bruhns and Mecklenburg⁵ (pp. 106–108) describe another experiment in which the crystallization of chrome alum resulted in raising porcelain fragments, loaded with weighted beaker-glasses, but they thought it essential that evaporation be carried to completion. The elevation of these beakers and similar evidences of pressure phenomena accompanying crystal growth they attribute to the “forces of adsorption and capillarity” and not to a “force of crystallization.” Becker and Day show that in this experiment the lifting action occurs in spite of capillary attraction rather than because of it, and that adsorption merely diminishes the rate of growth by delaying diffusion.⁸

As a result of their investigations Becker and Day conclude: (1) that there is “a linear force, apart from the volume expansion, exerted by growing crystals;” (2) that this force enables them to grow in directions in which growth is opposed by external force “notwithstanding unrestricted opportunity for growth in other directions; and (3) that the linear force thus exerted is of the order of magnitude of the breaking strength of the crystal.”⁹ “The crucial experiment [briefly described above] offered in support of this conclusion” is not, in the opinion of the present writer, decisive. It is significant that no growth occurs on the upper face of the crystal although it is subjected to less pressure than the lower face, and crystallographically both are the same. The elevation of the crystal is due to the fact that it rests directly on a thin layer of solution which is supersaturated by diffusion from without; and in this experiment the solution at the bottom of the crystallizing dish is of higher concentration than elsewhere. Furthermore, the effect of expansion in volume is not eliminated in this experiment, for alum separates from solution with increase in volume.

A crystal is enlarged through the addition of layers of material to its outer surfaces, and this takes place when these surfaces are in contact with a supersaturated solution. A very thin coating of impervious material is sufficient to prevent crystal growth. In the Becker and Day

experiment the supporting edges of the crystal rest directly on a thin layer of solution which is therefore under pressure. Now pressure tends to reduce the thickness of the supporting film to a minimum. With perfectly smooth parallel surfaces the minimum thickness of the separating film is perhaps equal to the diameter of the space occupied by a molecule of the liquid, and this is probably approximated in the present case, for deposition would be most rapid where the thickness of the supporting film is greatest. It would require great pressure to completely expel the solution from such a narrow space, and, if the solution is thus excluded, growth in a vertical direction would cease. The fact that this growth continues is proof that the solution is not expelled from under the crystal. Therefore when alum separates from solution and is added to the base of the crystal, the accompanying increase in volume must result in some elevation, irrespective of other causes.

The cavity or hollow formed on the under side of crystals in the experiment described above results from malnutrition, due to the slow rate of diffusion under the crystal as compared with the relatively rapid growth in other directions. The writer succeeded in eliminating this cavity by supplying the supersaturated solution through capillary openings under the base of small crystals. Since new material can be added only at the base, its area remains small and tall slender columns are formed.

The pressure phenomena observed during the growth of crystals have been attributed by the present writer "to the molecular forces associated with the separation of solids from solution and to the attraction and orientation of the physical molecules as they are brought into position on the surface of a growing crystal"⁷ (pp. 553-554). He suggested "that the force is due chiefly to the expansion in volume which accompanies the separation of most solids from solution, for, as yet, he has obtained no pressure effects during the crystallization of substances that separate from solution with decrease in volume."¹⁰ Recently, however, he has obtained definite evidence of pressure accompanying the crystallization of ammonium nitrate.¹¹ The experiment is described below.

A cup of porous porcelain was placed bottom up in a small jar half full of a concentrated solution of ammonium nitrate, and a piece of paraffine-coated card-board, cut to fit snugly around the cell, was cemented with paraffine to the top of the jar and to the walls of the cup. The jar was then placed in a desiccator containing calcium chloride, and allowed to stand undisturbed for nine months. The solution was drawn by capillary attraction to the upper and exposed walls of the cup where a crust was gradually formed by evaporation, but this crust was en-

larged chiefly or entirely through the addition of new material to the outer exposed surfaces, the solution reaching these surfaces through capillary pores in the crystalline mass. Under the card-board, however, a few long acicular crystals were formed on the surface of the cup, and these were gradually pushed outward by the addition of new material to their base. At one place the solution penetrated the card-board which was gradually split apart by the slow growth of a lens-shaped veinlet of finely crystalline salt about 3 mm. in thickness. The cup was not broken as in similar experiments with certain other salts that separate from solution with increase in volume.

The pressure phenomena observed in this experiment are explained as follows: Crystallization is retarded or prevented in supersaturated solutions which occupy small capillary or subcapillary spaces; therefore crystals may be supplied with material for growth by diffusion through solutions occupying such spaces, and the increase in volume due to the entrance and deposition of new material must result either in the expulsion of part of the solution or in the enlargement of the space occupied by the growing crystals. If the spaces occupied by the solution are relatively large, the solution will be gradually expelled as crystalline matter is deposited in its placè, but, on the other hand, if the spaces are sufficiently small, less force may be required to enlarge the space occupied by the growing crystals than is necessary to expel the solution. The diffusion of a solid through a solution and its separation therefrom are attributed to osmotic pressure and the relation between osmotic pressure and solution pressure. According to the writer's theory, the force observed in this experiment with ammonium nitrate is analogous to the pressure developed when an anhydrous salt, confined in a limited space, combines with water that has diffused as vapor through capillary openings.¹²

Molecular attraction between solid and liquid causes the thin layer of solution in contact with a crystal to adhere to it; and this contact film, on account of adsorption, is of different concentration from the bulk of the solution. Enlargement or solution of a crystal is brought about by the diffusion of dissolved substance across this layer. When the solution in contact with a crystal surface is supersaturated with respect to that surface, new material is deposited on the crystal, thus forcing the contact film to move outward from the growing crystal. If this film approaches a foreign body, growth in that direction is gradually retarded as the space through which diffusion must supply new material becomes more limited. Consequently growth will be more rapid in other directions, providing diffusion is not similarly restricted, and the

crystal will tend to surround the foreign body. Deposition of material between the crystal and the foreign body will continue, however, as long as diffusion can maintain supersaturation in the solution occupying this space; and, with continued crystal growth, the contact film must continue to be displaced. When this film comes in contact with the foreign body, any further growth must result in either (1) the displacement of the foreign body or (2) the rupture and expulsion of the film; and the outcome will depend on the resistance offered by the foreign body, the dimensions of the space occupied by solution and the mutual attraction between the molecules of the liquid and solids.

If the crystal is of a substance that goes into solution with decrease in volume, increased pressure will make it more soluble, thus increasing the degree of concentration requisite for further growth; but for those salts that have been tested a large change in pressure is required to produce an appreciable change in solubility. If the solubility of the foreign body is increased by pressure, it may be gradually removed in solution as the growing crystal replaces it.

The tendency of a crystal to assume a regular polyhedral form is important as a factor in the development of pressure during crystal growth only in so far as it affects the relative solubility of the crystal in different directions. A crystal growing in a solution of uniform concentration tends to build that form which is the least soluble under existing conditions, or, in other words, for which the total surface energy is a minimum. If the surface tension were the same in all directions this form would be a sphere, but in crystals the surface tension differs in different directions, or, on different faces, and is the same only on faces that are crystallographically the same. A solution that is in equilibrium with the flat face of a crystal will be supersaturated with respect to a concavity on the face and undersaturated with respect to a convexity. When a crystal having a concave face or an artificially truncated angle is placed in a solution of uniform concentration which is kept saturated with respect to the normal crystal faces, growth may be limited to a single direction until the imperfection is repaired, but growth can not continue indefinitely in a single direction as the superficial area and hence the surface energy would increase too rapidly in proportion to the volume. The variation in the solubility of a crystal in different directions is slight, and therefore it is probable that the difference is small in the pressure that may be developed in different directions by a growing crystal in contact on all its surfaces with a solution of uniform concentration. The surface tension on the different faces of a growing crystal probably depends on many factors, such as, the number of molecules per unit

area, their structure and orientation, pressure, temperature, and the composition of the solution. Hence, different faces may develop under different conditions of growth.

Most of the phenomena hitherto cited in support of the hypothesis that there is a 'linear force of crystallization' are to be explained by the fact that the growing crystals have been in contact with a supersaturated solution in only one direction or that the concentration of the solution has been greater in one direction than in others. It is probable that the pressure effects observed during crystallization are due chiefly to the separation of solid matter from solution rather than to the growth of crystals, and, under favorable conditions, the pressure developed in this way may greatly exceed the crushing strength of the substance.

Crystals grow in directions in which external forces oppose growth whenever the surfaces under pressure are in contact with a film of supersaturated solution, and it is possible to supply the material for growth by slow diffusion through subcapillary spaces, as great resistance is offered to the expulsion of solution from such openings. The conditions requisite for the growth of crystals under pressure commonly obtain in the rocks of the earth's crust, and many phenomena connected with the metamorphism of rocks, the growth of concretions, and the formation of mineral deposits are difficult of explanation under any other hypothesis than that growing crystals have made room for themselves by exerting pressure on the surrounding material.

¹ Lavalle, J., *Paris, C.-R. Acad. Sci.*, **36**, 1853, (493).

² Kopp, H., *Ann. Chem. Pharm., Leipzig*, **94**, 1855, (124).

³ Lehmann, O., *Molekularphysik*, **1**, (342), Leipzig, 1888.

⁴ Becker, G. F., and Day, A. L., *Proc. Washington Acad. Sci.*, **7**, 1905, (285-287).

⁵ Bruhns, W., and Mecklenburg, W., *Jahresber. Niedersächs. geol. Ver. Hanover*, **6**, 1913, (22-115).

⁶ Becker, G. F., and Day, A. L., *Chicago, J. Geol., Univ. Chic.*, **24**, 1916, (315-325).

⁷ Taber, S., *New Haven, Amer. J. Sci.*, (Ser. 4), **41**, 1916, (535).

⁸ Becker, G. F. and Day, A. L., *Chicago, J. Geol., Univ. Chic.*, **24**, 1916, (325-329).

⁹ *Ibid.*, (313).

¹⁰ Taber, Stephen, The origin of veins of the asbestiform minerals, these Proceedings, **2**, 1916, (662).

¹¹ According to Traube ammonium nitrate goes into solution with expansion in volume; *Zs. anorg. Chem., Hamburg*, **3**, 1892 (1). This reference cited in G. P. Baxter's Changes in volume upon solution in water of the salts of the alkalis, *J. Amer. Chem. Soc., Easton, Pa.*, **33**, 1911, (923).

¹² For description of this experiment see The genesis of asbestos and asbestiform minerals by Stephen Taber, *Bull. Amer. Inst. Min. Eng.* No. 119, p. 1987, Nov. 1916.